Defining the Materials Issues and Research for Ultra-Supercritical Steam Turbines

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ABSTRACT

Current state-of-the-art coal-fired supercritical steam power plants operate with high-pressure turbine inlet steam temperatures close to 600°C. The best of the recently developed and commercialized advanced 9-12Cr martensitic-ferritic steels may allow prolonged use at temperatures to about 620°C, but such steels are probably close to their inherent upper temperature limit. Further increase in the temperature capability of advanced steam turbines will certainly require the use of Ni-based superalloys and system redesign. The U.S. Department of Energy (DOE) has recently undertaken a concerted effort to qualify ultra-supercritical boiler tubing and piping alloys for 720/760°C steam for increased efficiency and reduced emissions. It is, therefore, necessary to also develop the corresponding USC steam turbine materials program, so that turbines capable of reliable operation at such conditions are also available. In FY2005, the Oak Ridge National Laboratory (ORNL) and the National Energy Technology Laboratory (NETL) assessed the materials needed for ultra-supercritical (USC) steam turbines, balancing both technical and business considerations. These efforts have addressed an expanded portfolio of alloys, which includes austenitic stainless steels and alloys, in addition to various Ni-based superalloys for critical turbine components. Last year, ORNL conducted sites visits to the U.S. turbine original equipment manufacturers (OEMs) to develop the consensus on this materials program and its needs. In FY2005 ORNL was a collaborative partner with Energy Industries of Ohio (EIO) and EPRI in developing the USC Steam Turbine Consortium and the proposal which won the DOE/NETL RFP on Development of Technologies and Capabilities for Clean Coal Energy Resources.

INTRODUCTION

Several recent papers make the need for new alloys with higher creep strength and more oxidation resistance clear for new, highly efficient and cleaner, ultrasupercritical (USC) steam power plants operating at 650-750^{o}C [1-4] (Fig. 1). While USC boiler materials must also be construction-code approved and able to withstand the severe fire-side corrosion environment, those constraints are relaxed somewhat for USC steam turbines [3,4]. There are a range of Ni- and Ni-/Co-based superalloys that show attractive properties for USC steam turbine applications. However, the need for cost-effective performance and economic considerations mean that more affordable materials, like austenitic stainless steels and alloys, must also be considered, where appropriate, in these advanced steam turbine systems. The logical place to consider such materials is in the casing or other massive components, and the recently developed CF8C-Plus cast austenitic stainless steel appears to a candidate for these applications.

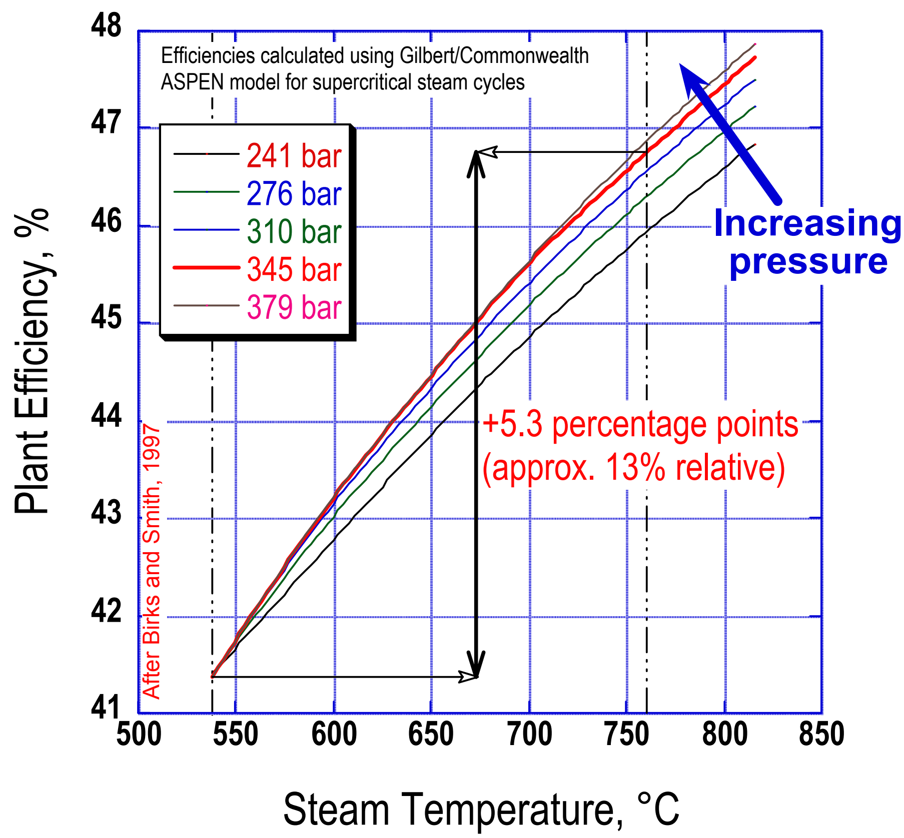

Figure 1. Effect of increasing steam temperature and pressure on cycle efficiency.

Defining the Materials Issues for USC Steam Turbines

The requirements for advanced steam turbine materials include commercial or near-commercial availability, sufficient strength, steam oxidation resistance and temperature capability at 650-750°C, appropriate physical properties (ie. thermal expansion and conductivity) for the part/component being considered, fabricability, and acceptable cost. While there is some debate as to the actually upper temperature limit of commercial advanced 9-12Cr ferritic/martensitic steels, it does appear that for temperatures of 625-650°C or above, them do not have adequate strength or steam oxidation resistance, and must be replaced by alloys with more performance and reliability at higher temperatures [1-4] (Figs. 2 and 3).

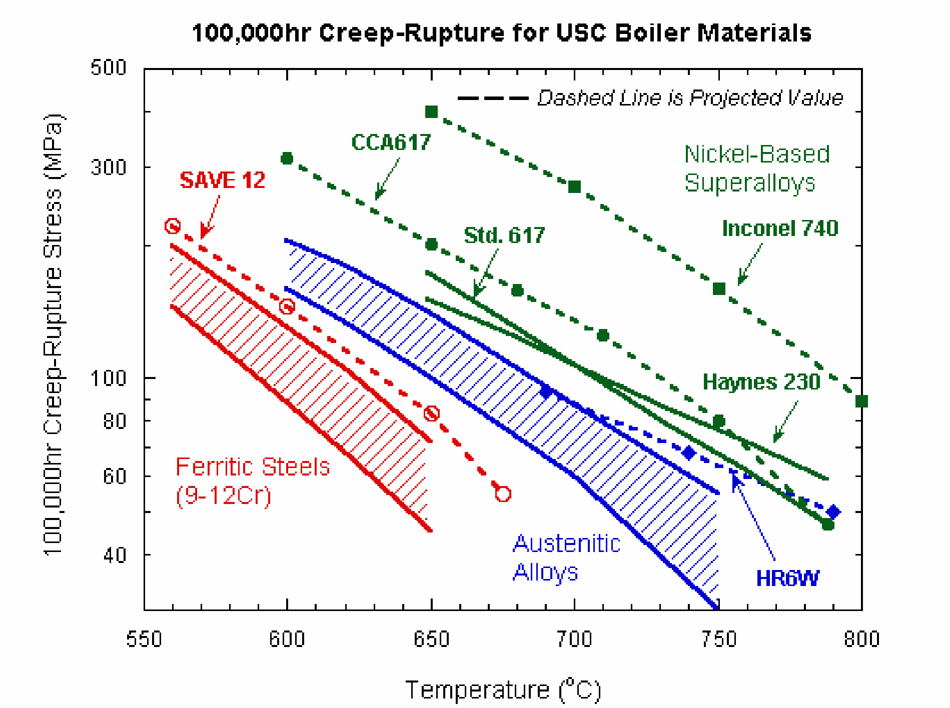

Figure 2. 100,000 hour creep-rupture strength for different material classes of alloys for potential USC steam boiler components.

Detailed engineering designs do not now exist for USC steam turbines. Therefore, the starting point for such new and different systems is to list the main components of interest that must be present in any kind of turbine, then specify the likely temperature

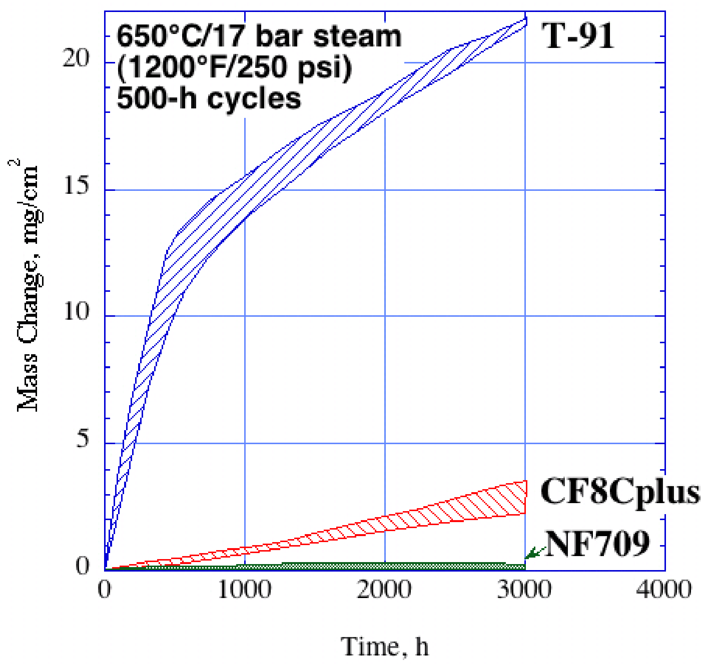

Figure 3 – Mass change oxidation kinetics data for testing of 9Cr-1MoVNb (T-91) martensitic/ferritic steel, and two austenitic stainless steels, the new cast CF8C-Plus (Fe-19Cr-12Ni NbMnN and NF709 (Fe-20Cr-25Ni MoNbN), at ORNL in steam at 650°C.

and steam pressure at which they will operate, and then to list the alloys that can be considered for such components. Several recent review papers list alloys for main components, including turbine casing/shell (including the steam chest), cyclinders and valve bodies, bolting, turbine rotors and discs, and vanes and blades [1-4]. Both long-term creep-strength and oxidation resistance make some austenitic stainless steels and various superalloys necessary choices over the 9-12 Cr steels used for steam turbines today (Figs 2 and 3).

Materials for Casings and Shells

Steam turbine casings are typically large structures, with complex shapes that must provide the pressure containment for the steam turbine. Because turbine casing components are massive, their cost has a strong impact on the overall cost of the turbine. The materials used currently for inner and outer casings are the 1-2CrMo steels, usually as castings. The temperature limit of these alloys in this application is approximately 566°C, mainly due to their resistance to steam oxidation. For higher temperatures, cast 9Cr-1MoVNb alloys are considered to be adequate in terms of strength capabilities to 593°C, while the 12Cr steels in either cast or forged form currently appear to be limited to 620°C, assuming acceptable steam oxidation resistance. Casings made of cast martensitic/ferritic steels must still be heat-treated and tempered to produce the best combination of high temperature strength and ductile-to-brittle transition temperature (DBTT) behavior at low temperature.

In terms of strength, the next step up in cast alloys for casings logically would be an austenitic stainless steel: cast 316 was used in Eddystone. However, problems experience with that cast stainless steel, such as thermal fatigue cracking, led the industry to discontinue use of such alloys in steam turbines. Recent modifications to cast 347H (CF8C) stainless steel have resulted in development of a new steel, CF8C-Plus [4] (Table 1) developed by ORNL and Caterpillar, with creep strength better than NF709 and Super304H, and close to that of the Ni-based superalloy 617 (Fig. 4). The possibility of using an austenitic stainless steel in significantly thinner sections (due both to better castability and much better strength) has the potential for reducing thermal fatigue sensitivity compared to earlier cast stainless steels. This new properties data suggests this class of alloys should be reconsidered for steam turbines.

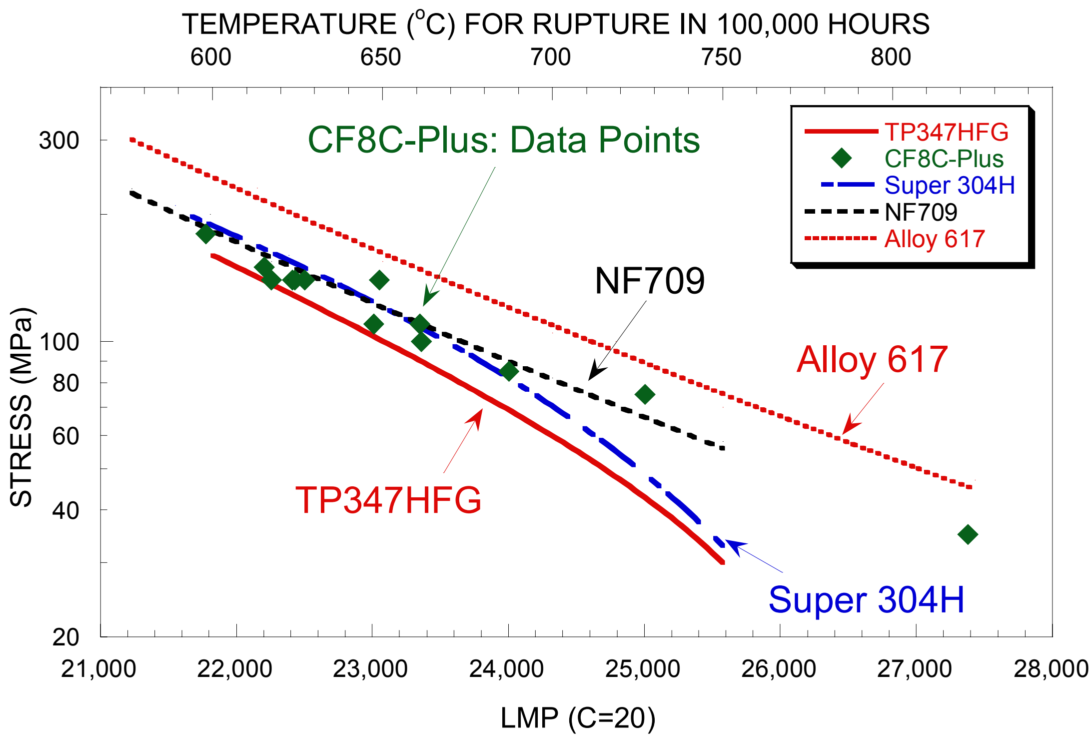

Figure 4 – Plot of creep rupture stress versus Larson-Miller Parameter (LMP) for cast CF8C-Plus steel, and various wrought alloys including TP347HFG and Super 304H stainless steels, NF709 stainless alloy, and superalloy 617. The upper axis reflects extraplotion to use temperature for rupture life of 100,000h.

The CF8C-Plus steel was developed based on a unique "engineered microstructure" method to be have a stable austenite matrix phase (free of delta ferrite) for resistance to the aging-induced sigma phase embrittlement that plagues standard CF8C steel [4]. The high temperature creep strength of CF8C-Plus steel is based on stable nano-scale dispersions of NbC within the grains. CF8C-Plus steel also has much higher creep-rupture ductility (despite its higher strength) due to the lack of sigma or other embrittling precipitate phases (Figure 5). CF8C-Plus also has outstanding fatigue and thermal fatigue resistance. These properties are achieved in the as-cast condition without the need for any additional heat-treatments, which is a benefit for large

castings. CF8C-Plus also has good castability, and in July 2004, MetalTek International used it to cast a large gas turbine end-cover component (6,700 lb) of this new steel. Steam oxidation behavior of CF8C-Plus steel is much better than 9-12Cr martensitic/ferritic steel 650°C (Fig. 3), and should be comparable to other austenitic stainless steels and alloys to about 700°C or slightly higher.

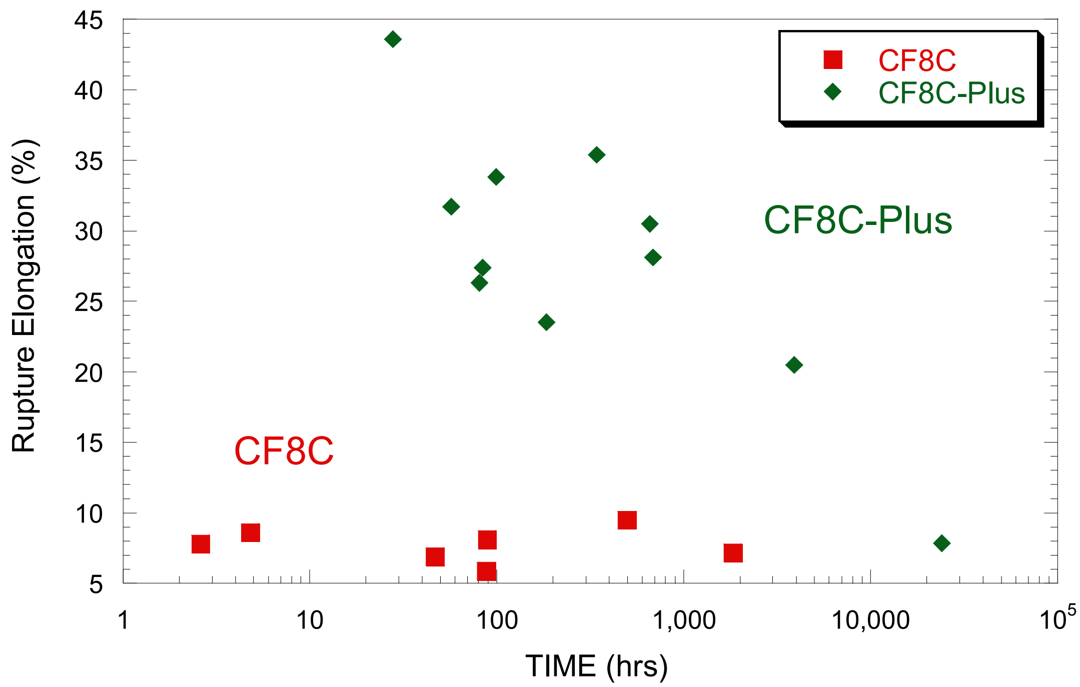

Figure 5 - A plot of creep rupture ductility versus rupture time for standard CF8C steel and new CF8C-Plus steel creep tested at 700-850°C. CF8C-Plus has consistently higher ductility despite nearly twice the creep strength because it does not form embrittling sigma-phase.

For the highest temperatures, Ni-based alloys will be required, and the question will be whether adequate strengthening can be developed in solid-solution strengthened cast alloys, or whether age-hardenable wrought alloys will be needed. The candidate alloys chosen for evaluation by the European AD700 program included both Fe-based superalloys and Ni-base alloys: 155, 230, 263, 617, 625, 706, 718, 901, and Waspaloy. For castings, uncertainties in extrapolating properties measured for small laboratory heats to those of large components mandate that either full-scale or prototypical components are used for testing. With present foundry practice in the U.S., the preference would be to make these components from forgings from Europe and Japan to ensure reliability, whereas using cast shapes would be a considerably less expensive route. Therefore, there are strong incentives to minimize the temperature requirement for the outer shell components by design, and to improve the quality of large 12-Cr martensitic/ferritic and austenitic stainless steel castings. There is considerable experience in producing castings of Inconel 625 and, in the European programs, data were generated from trial castings of both Inconel alloys 617 and 625. A step-block casting geometry was used for the prototypical component, and a full-scale valve chest was cast in alloy 617. Considerable experience also

exists for large forgings of alloys such as IN 706 and 718, and long-term creep data are available for the wrought forms of alloys such as 617, 625 and Haynes 230. Only a modified version of 617 (CCA617), and the new alloy, Inconel 740, appear to meet the strength and creep-rupture criteria for the 760°C goal of the U.S. USC steam boiler program (Fig. 2).

The major materials needs are for Ni-based alloys for operation at 760°C with (i) adequate creep rupture strength; (ii) ability to cast them into the required size and shape, and to inspect for defects; and (iii) ability to perform initial fabrication welding (on cast or wrought forms, including dissimilar metal welds), and to make repair welds on aged material. Considerable experimental effort to generate data is required, and will involve the development of rupture, creep, and rupture ductility relationships for these materials. Substantial progress has been made in Europe for both processing methods and procurement of design data. The data requirements include long-term creep behavior of castings, weld metal, similar and dissimilar metal weldments, as well as the effects of aging (and steam oxidation) on the microstructure, hence strength/toughness of these materials.

Bolting

The major requirements for bolting materials are high resistance to stress relaxation (ageing characteristics) at temperatures that can range up to the maximum steam temperature experienced by the casing for the hot gas path; thermal expansion characteristics compatible with those of the structure to be bolted; and low notch sensitivity. There is a wide range of alloys available for this application, and the specific alloy selection depends for the most part on the criteria used by each manufacturer. In current usage, ferritic steels (variants of type 422 steel) are used up to approximately 566°C, and the Ni-base Nimonic alloys are typically used for higher temperatures. Based on world-wide experience, Nimonic 80A and a few proprietary alloys (such as Refractaloy 26) appear to be good candidates for temperatures up to 593°C. For the bolting needs to 720°C in the European program, and to 760°C in the U.S. USC Steam Program, Ni-based alloys will be required and, as shown in Table 2, there is a range of candidates, with Waspaloy apparently being preferred up to 700/720°C. Two other relatively new alloys can be considered for bolting, based on their combination of creep strength and ductility, namely Inconel 740 and Allvac 718-Plus [2] (see Table 2). The Allvac 718-Plus was developed as an alloy intermediate in composition between the standard alloy 718 and Waspaloy, with more temperature capability, and more creep strength than either at 700°C.

The major property data needed for these materials are: creep-relaxation behavior; effect of component size on microstructure; and compatibility with steam at the higher temperatures of interest. Long-term creep data are available for a number of these alloys, including U-700, U-710, U720 variants, Nimonic alloys 105 and 115. The required stress relaxation properties can be calculated from the measured creep properties using creep law equations, and/or extrapolated to long times using parametric methods. It is considered important to determine the effect of bolt diameter on microstructural characteristics such as grain size, gamma prime content, and chemical segregation.

Overall, for bolting, the choice of materials appears to be relatively straightforward. There do not appear to be significant manufacturing issues, since these alloys are available as bar stock

suitable for rolling or grinding to shape. Similar requirements exist for bolting in combustion gas turbines, although there may be some scale-up issues to be addressed.

Rotors/discs

The HP rotor/discs will have to handle the highest steam conditions, so that a Ni-based alloy will be required for temperatures greater than 620°C; a mitigating factor is that this component may be relatively small (depending on the overall steam turbine design). The IP rotor handles steam at the maximum system temperature, but at reduced pressure. The strength requirement may be relaxed compared to the HP rotor, but the issue of oxidation in steam remains. Materials selection for this component may be a critical issue because of its size. For maximum overall efficiency, it would be desirable also to increase the temperature of the steam entering the low-pressure (LP) rotor. This component will require a NiCrMoV steel of the type in current use, but which is likely to be susceptible to temper embrittlement in this application (>316°C). Resort may be made to cooling of this rotor, or to alloy modification. Alternatively, metallurgical processing changes may be introduced to reduce the susceptibility to temperature embrittlement (by reducing the levels of P, Sn, Mn, Si).

The alloys most commonly used for steam turbine rotors and/or discs are the CrMoVWNbN steels, which can vary in chromium content from 1-13% depending on the preference of individual manufacturers. These alloys are widely used up to a temperature limit of about 566°C, and the higher-W, lower-Nb and -C versions are capable of 593°C. The issues for alloys for higher-temperature use are similar to those for materials for steam piping. Versions of these ferritic steels, based on the advanced 9-12% Cr compositions, are already in service at steam temperatures of 600°C, and it is expected that they will be usable to approximately 620°C (and possibly 650°C). Ni-based alloys will be required for the higher temperatures, and candidates include Inconel alloys 617, 625, and the new 740 and 718Plus alloys, and Haynes 230. Except for 740 and 718Plus, these alloys are approved by the ASME Boiler and Pressure Vessel Code (not required for rotors), so that a significant design database exists for them, but more complex mechanical data, such as creep-fatigue and thermal-fatigue, is needed.

The main issues for rotors/discs concern manufacturing, especially the capability to produce large castings and forgings. With modern secondary steel making practices, such as ladle furnaces, electroslag remelting to control freezing segregation, and control of the sulfur and phosphorus levels in the alloy, very large rotors now can be produced, but experience is related mostly to Cr-Mo-V alloys (used in current 541-566°C plants), and for 12 Cr alloys (needed for advanced steam cycles to 620°C). A further major issue, depending on the design approach used, is the need for developing the techniques required for making dissimilar metal welds when Ni-based alloys are used for the HP turbine, and the lower alloy/ferritic steels used for the IP turbine.

Blading

The current supercritical steam plants in the U.S. typically use vanes and blades made from 12 Cr ferritic steels such as type 422, or proprietary alloys of similar composition. For higher temperatures there is available a wide choice of wrought Ni-based alloys, for which a substantial

design database exists from their application in gas turbines. For operation with steam at 760°C, it is considered likely that materials new to steam use will be necessary for at least four stages in the HP turbine, and probably also in the IP turbine. The choice of blading material will depend on (i) the temperature of the rotor, hence on the thermal expansion characteristics of the component material, and (ii) the size and shape of the blade, which will be designed using computational fluid dynamics modeling. Steam compatability data for these materials will be required. Recent research data on moisture effects on oxidation suggest that it will be important to have higher-Cr levels in these alloys to avoid preferential internal attack in steam. Consideration needs to be given to the problem of solid particle erosion from entrained particles of oxide scale that may exfoliate from the superheater and reheater tubing. While this problem may not be greater in USC turbines than problems encountered in current steam turbines, it will be prudent to ensure that erosion-mitigating coatings technology is available and compatible with new high-temperature blading materials.

Overall, there do not appear to be significant manufacturing issues for blading alloys, especially given the gas turbine experience and the fact that these components are largely made in the U.S. However, effort will be necessary to ensure that current manufacturing procedures have the capability to produce the required components from the alloys chosen, and that processing data are available for producing the large blades that may be needed in some steam turbine designs.

Testing and Life Prediction

While these topics are beyond the scope of this review, it is important to appreciate that the efforts to obtain high-quality databases for design at high temperatures will be costly and time-consuming. Accordingly, it will be necessary to make the best and most appropriate use accelerated methods where possible. Also modeling methods to predict materials performance, for example, in creep and fatigue, will enable testing to be targeted on the most critical conditions, thereby reducing the overall size (and cost) of mechanical test programs. An import early program step will be to validate the various models to ensure the level of reliability of the predicted properties. Similarly, life prediction techniques will be important for enabling the life of critical components to be estimated, thereby limiting the need to depend only on large-scale testing.

Summary of Materials Issues and Research Needs

The materials issues resulting from the need for turbines to operate under ultra-supercritical steam conditions are summarized in Table 3, which attempts to provide a simple ranking of the level of effort needed to provide materials choices for three target steam temperatures, 620, 700, and 760°C. In the Table, the level of effort required is given a numerical rating, from 1-5, where '5' suggests that considerable research and development will be needed, while a ranking of '1' indicates that most of the capability required is already available.

Input from U.S. Turbine OEMs

Last year, ORNL conducted sites visits to the U.S. turbine original equipment manufacturers (OEMs), Siemens-Westinghouse, Alstom and General Electric, to develop the consensus presented here on the USC steam turbine materials program and its needs. In FY2005 ORNL

was a collaborative partner with Energy Industries of Ohio (EIO) and EPRI in helping to developing the USC Steam Turbine Consortium and the proposal which won the DOE/NETL RFP on Development of Technologies and Capabilities for Clean Coal Energy Resources.

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Table 1. Chemical Compositions of Alloys Mentioned in the Text (in weight percent)

Alloy	Fe	Ni	C	Co	Cr	Nb	Mo	W	Ti	Al
T92	Bal	0.4	0.1	—	9	0.1	0.5	1.8	—	—
Type 422	Bal	0.7	0.22	—	12	—	1	1	—	—
T122	Bal	0.3	0.1	—	12	0.05	0.4	2	—	—
Nimonic 901	Bal	42.5	0.04	1	12.5	—	6	—	3	0.3
A286	Bal	26	0.05	—	15	—	1	—	—	2
Type 316	Bal	11-14	0.06	—	16-18	—	2-3	—	—	—
Type 347H	Bal	10	0.08	—	18	0.8	—	—	—	—
NF709[1]	Bal	25	0.1	—	21	0.3	1.5	—	—	—
Haynes 120[1]	Bal	32	0.05	—	25	0.7	2	—	—	—
Refractaloy 26	Bal	36	0.03	19	18	—	3	—	2.6	—
CF8C	Bal	10	0.08	—	19.5	0.85	—	—	—	—
CF8C-Plus[2]	Bal	12.5	0.1	—	19	0.8	0.3	—	—	—
N155	Bal	20	0.15	20	21	—	3	2.5	—	—
Haynes 230	3	Bal	0.1	5	22	—	2	14	—	0.3
Hastelloy X	18.5	Bal	0.1	1.5	22	—	9	0.6	—	—
CCA617	0.7	Bal	0.06	12	22	—	9	—	0.4	1.2
Inconel 625	3	Bal	0.05	—	22	4	9	0.2	0.2	0.2
Inconel 740	2	Bal	0.07	20	24	2	0.5	—	2	1
IN706	40	Bal	0.03	0.5	16	—	0.5	—	2	0.2
IN718	18	Bal	0.04	—	19	5	3	—	1	0.5
Allvac 718Plus	10	Bal	0.025	9	17.5	5.4	2.7	1	0.7	1.5
IN939	—	Bal	0.15	19	22	1	—	2	3.7	1.9
Nimonic 80A	5	Bal	0.1	2	20	—	—	—	3	2
Nimonic 105	1	Bal	0.2	20	15	—	5	—	2	4
Nimonic 115	—	Bal	0.2	15	15	—	4	—	4	5
Nimonic 263	1	Bal	0.06	20	20	—	6	—	2	0.5
U700	1	Bal	0.15	18.5	15	—	5.2	—	3.5	4.25
U710	—	Bal	0.07	15	18	—	3	1.5	5	2.5
U720	—	Bal	0.01	14.7	16	—	3	1.25	5	2.5
Waspaloy	2	Bal	0.07	14	20	—	4	—	3	1

1- contains >0.1 N
2- contains additions of Mn and N

Table 2. Materials Selection for the High-Pressure Steam Turbine

Component	566°C	620°C	700°C	760°C
Casings/Shells (valves; steam chests; nozzle box; cylinders)	CrMoV (cast) 10CrMoVNb	9-10%Cr(W) 12CrW(Co) CrMoWVNbN	CF8C-Plus CCA617 Inconel 625 IN 718 Nimonic 263	CCA617 Inconel 740 CF8C-Plus (?)
Bolting	422 9-12%CrMoV Nimonic 80A IN718	9-12%CrMoV A286 IN718	Nimonic 105 Nimonic 115 Waspaloy IN718 Allvac 718Plus	U700 U710 U720 Nimonic 105 Nimonic 115
Rotors/Discs	1CrMoV 12CrMoVNbN 26NiCrMoV11 5	9-12%CrWCo 12CrMoWVNbN	CCA617 Inconel 625 Haynes 230 Inconel 740	CCA617 Inconel 740
Vanes/Blades	422 10CrMoVNbN	9-12%CrWCo	Wrought Ni-base	Wrought Ni-base
Piping	P22	P92	CCA617	Inconel 740

Table 3. Ranking of Overall Materials Needs

Component		Steam Temperature, °C			Major Issues
		620	700	760	
Casing	Materials	3	4	5	Design data; improved alloys
	Manufacturing	3	5	5	Cast vs wrought; process control
Bolting	Materials	1	3	3	Design data; design procedures
	Manufacturing	1	1	1	
Rotors/Discs	Materials	3	3	5	Design data; weldability
	Manufacturing	4	4	4	Melting and fabrication
Vanes/Blades	Materials	3	4	4	Improved austenitics; Ni-base alloys
	Manufacturing	3	4	4	Forging process (modeling)